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APPLICATION OF BALANCING TABS TO AILERONS

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APPLICATION OF BALANCING TABS TO AILERONS

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SUMMARY

An analysis has been made to determine the characteristics required of a balancing-tab system for ailerons in order to reduce the aileron stick forces to any desired magnitude. A series of calculations has been made, based on section data, to determine balancing-tab systems of various chord tabs and ailerons that will give, for a particular airplane, zero rate of change of aileron hinge moment with aileron deflection and yet will produce the same maximum rate of roll as a plain, unbalanced 15-percent-chord aileron of the same span. The effect of rolling velocity and of the forces in the tab link on the aileron hinge moments have been included in the calculations.

INTRODUCTION

The use of a conventional balancing tab on ailerons presents a possible means of reducing the aileron stick forces. Because the deflection of the balancing tab must be in opposition to the aileron deflection in order to reduce the hinge moments of a plain aileron, the lift effectiveness of the combination will be less than that of the plain aileron. In order to be capable of producing the same rate of roll as a given plain aileron, therefore, an aileron with a balancing tab must be deflected farther than the plain aileron or its chord or its span must be greater than that of the plain aileron. Because, throughout some range of aileron deflections, tabs become relatively ineffective in reducing aileron hinge moments when they are deflected more than 20°, the aileron balancing tab must be designed to avoid deflection beyond its effective limit. The moment supplied to the flap by the tab linkage and also the effect of rolling velocity must be included in the calculations for the proper tab arrangement to give the desired aileron hinge-moment characteristics. The following analysis has been undertaken in order to determine more exactly how these general considerations for an aileron balancing-tab system are interrelated and to serve as a basis of computations for designing such a system.

SYMBOLS

α angle of attack

$\Delta\alpha$ effective change in angle of attack over aileron portion of wing due to rolling velocity

δ_a aileron deflection relative to wing

δ_t tab deflection relative to aileron

c_a aileron chord behind hinge axis

c_t tab chord behind hinge axis

c wing chord

b wing span

$\bar{b}$ effective wing span used to calculate $\Delta\alpha$

p rolling velocity

V forward velocity

d moment arm of tab link about tab hinge axis

λ angle between tab link and line joining centers of aileron and tab hinge axes (fig. 1)

k factor proportionate to airplane damping in roll

C_L lift coefficient

C_h hinge-moment coefficient

$$C_{L_\alpha} = \left(\frac{\partial C_L}{\partial \alpha}\right)_\delta$$

$$C_{h_\alpha} = \left(\frac{\partial C_h}{\partial \alpha}\right)_\delta$$

$$C_{h_\delta} = \left(\frac{\partial C_h}{\partial \delta}\right)_\alpha$$

Subscripts:

o original aileron

a aileron

t tab

max maximum

Quantities with a single prime mark refer to effective values for aileron-tab combination when the airplane is rolling.

ANALYSIS

Let it be assumed for the purposes of analysis that it is desired to replace the original plain ailerons of an airplane with ailerons of the same span equipped with a full-span balancing tab to give any desired hinge-moment-coefficient slope $C_{h_{\delta_a}}{}'$. The new aileron must be capable of producing the same maximum rate of roll as the original aileron.

In general, the hinge-moment coefficient of an aileron equipped with a balancing tab can be expressed by the following relation:

$$C_{h_a} = C_{h_{a_o}} + C_{h_{a_\alpha}}\alpha' + C_{h_{a_{\delta_a}}}\delta_a + C_{h_{a_{\delta_t}}}\delta_t - \left(\frac{c_t}{c_a}\right)^2 \left(1 + \frac{c_a - c_t}{d} \sin \lambda\right) C_{h_t} \qquad (1)$$

where

$$C_{h_t} = C_{h_{t_o}} + C_{h_{t_\alpha}}\alpha' + C_{h_{t_{\delta_a}}}\delta_a + C_{h_{t_{\delta_t}}}\delta_t \qquad (2)$$

The last term in equation (1) is the contribution to the aileron hinge-moment coefficient by the force in the tab link. This contribution must be computed because, in normal wind-tunnel procedure, the aileron hinge moment is measured with the tab link fastened to the aileron. On the airplane, however, the tab link is fastened to the wing proper. In flight, therefore, because of the tab link, the aileron hinge moment will be different from that measured in the tunnel. The sign of λ, the angle between the line joining the aileron and tab hinge axes and the tab link can be easily determined by a simple sketch, such as figure 1. When the ratio of tab deflection to aileron deflection is -1 (fig. 1(a)), the linkage system is a parallelogram, λ equals zero, and the aileron hinge moment is reduced (algebraically but not necessarily numerically) by the hinge moment of the tab. When the deflection ratio is greater than -1 (fig. 1(b)), the linkage system converges toward the trailing edge, λ is positive, and the increment of aileron hinge moment is greater than the tab hinge moment. On the other hand, when the deflection ratio is less than -1 (fig. 1(c)), the linkage system converges toward the aileron nose, λ is negative, and the increment of aileron hinge moment is less than the tab hinge moment. This effect is purely mechanical and is in addition to any aerodynamic effect the tab deflection may have on the aileron hinge moment. For nonparallel linkage systems the angle λ is a function of the aileron deflection. An analysis of differential linkage systems similar to those generally used to operate balancing tabs is given in reference 1.

In order to simplify the calculations of this analysis, the ratio of tab deflection to aileron deflection is assumed to be -1. The value of λ, therefore, is zero and the aileron hinge moment is algebraically reduced by the hinge moment of the tab. When the required ratio of tab to aileron deflection is calculated, the resulting hinge-moment slope C_{h_δ}' must be interpreted as being slightly greater or slightly less than the design value because of a small deviation from the assumed effect of the tab link. With a balancing tab operated by a parallel linkage system, equation (1), therefore, may be rewritten:

$$C_{h_a} = C_{h_{a_0}} + C_{h_{a_\alpha}}\alpha' + C_{h_{a_{\delta_a}}}\delta_a + C_{h_{a_{\delta_t}}}\delta_t - \left(\frac{c_t}{c_a}\right)^2 C_{h_t} \qquad (3)$$

and, when combined with equation (2), the expression for

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the tab hinge-moment coefficient becomes:

$$C_{h_a} = \left[C_{h_{a_o}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_o}}\right] + \left[C_{h_{a_\alpha}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_\alpha}}\right]\alpha'$$

$$+ \left[C_{h_{a_{\delta_a}}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_{\delta_a}}}\right]\delta_a + \left[C_{h_{a_{\delta_t}}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_{\delta_t}}}\right]\delta_t \qquad (4)$$

For simplicity, let the over-all hinge-moment characteristics of the aileron corrected for the effect of a parallel tab-linkage system be:

$$\left.\begin{aligned} C_{h_o}'' &= C_{h_{a_o}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_o}} \\ C_{h_\alpha}'' &= C_{h_{a_\alpha}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_\alpha}} \\ C_{h_{\delta_a}}'' &= C_{h_{a_{\delta_a}}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_{\delta_a}}} \\ C_{h_{\delta_t}}'' &= C_{h_{a_{\delta_t}}} - \left(\frac{c_t}{c_a}\right)^2 C_{h_{t_{\delta_t}}} \end{aligned}\right\} \qquad (5)$$

Thus equation (4) may be rewritten as:

$$C_{h_a} = C_{h_o}'' + C_{h_\alpha}''\alpha' + C_{h_{\delta_a}}''\delta_a + C_{h_{\delta_t}}''\delta_t \qquad (6)$$

Due to rolling velocity p:

$$\alpha' = \alpha + \left(\frac{\partial\alpha}{\partial\delta_a}\right)_p \delta_a \qquad (7)$$

where $\left(\frac{\partial \alpha}{\partial \delta_a}\right)$ is the rate of change of angle of attack of the aileron with aileron deflection caused by rolling velocity. Equation (6) becomes

$$C_{h_a} = C_{h_o}'' + C_{h_\alpha}'' \alpha + \left[C_{h_\alpha}'' \left(\frac{\partial \alpha}{\partial \delta_a}\right)_p + C_{h_{\delta_a}}''\right] \delta_a + C_{h_{\delta_t}}'' \delta_t \tag{8}$$

If $\delta_t = f(\delta_a)$, the effective slope $C_{h_{\delta_a}}'$ may be found by differentiating equation (8). Thus

$$C_{h_{\delta_a}}' = C_{h_\alpha}'' \left(\frac{\partial \alpha}{\partial \delta_a}\right)_p + C_{h_{\delta_a}}'' + C_{h_{\delta_t}}'' \frac{\partial \delta_t}{\partial \delta_a} \tag{9}$$

The required rate of tab deflection to give any desired $C_{h_{\delta_a}}'$ is

$$\frac{\partial \delta_t}{\partial \delta_a} = \frac{C_{h_{\delta_a}}' - C_{h_\alpha}'' \left(\frac{\partial \alpha}{\partial \delta_a}\right)_p - C_{h_{\delta_a}}''}{C_{h_{\delta_t}}''} \tag{10}$$

It is now necessary to find an expression for $\left(\frac{\partial \alpha}{\partial \delta_a}\right)_p$ for the new aileron in terms of known characteristics of the original aileron. Thus,

$$\left(\frac{\partial \alpha}{\partial \delta_a}\right)_p = \left(\frac{\partial \alpha}{\partial \frac{pb}{2V}}\right) \left(\frac{\partial \frac{pb}{2V}}{\partial \delta_a}\right) \tag{11}$$

It can be shown that the effective change in angle of attack of the aileron (in deg) caused by rolling velocity is:

$$\left.\begin{aligned}\Delta\alpha &= -\tan^{-1}\frac{p\overline{b}}{2V}\\ &= -\left(\tan^{-1}\frac{pb}{2V}\right)\left(\frac{\overline{b}}{b}\right)\\ &= -57.3\left(\frac{pb}{2V}\right)\left(\frac{\overline{b}}{b}\right)\text{ (approx.)}\end{aligned}\right\}\tag{12}$$

The effective wing span $\overline{b}$ used in equation (12) has been determined from span-load distribution calculations (reference 2). When the aileron chord is a constant proportion of the wing chord along the span, $\overline{b}$ was found to be approximately equal to the wing span between points located 10 percent of the individual aileron span outboard of the inboard ends of the two ailerons. Thus from equation (12):

$$\frac{\partial\alpha}{\partial\frac{pb}{2V}} = -57.3\,\frac{\overline{b}}{b}\tag{13}$$

For any particular airplane the rate of roll is dependent upon the increment of lift (rolling moment) produced by the ailerons and the damping in roll of the airplane, but the damping in roll is independent of the aileron characteristics. Thus,

$$\frac{pb}{2V} = k\left(\frac{\partial\alpha}{\partial\delta_a}\right)_{C_L} C_{L_\alpha}\,\delta_a\tag{14}$$

where k is a factor dependent upon the damping in roll and may be evaluated for any particular airplane with any aileron in terms of known characteristics of the airplane with the original ailerons. Therefore, from equation (14),

$$k = \frac{\left(\frac{pb}{2V}\right)_o}{C_{L_\alpha}\left(\frac{\partial\alpha}{\delta_{a_o}}\right)_{C_E}\quad\delta_{a_o}}\tag{15}$$

Thus, equation (14) becomes for any new aileron,

$$\frac{pb}{2V} = \frac{\left(\frac{pb}{2V}\right)_o}{C_{L_\alpha}\left(\frac{\partial \alpha}{\partial \delta_{a_o}}\right)_{C_L} \delta_{a_o}} C_{L_\alpha}\left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L}' \delta_a \tag{16}$$

And, for any aileron on the given airplane,

$$\frac{\partial \frac{pb}{2V}}{\partial \delta_a} = \frac{\left(\frac{pb}{2V}\right)_o}{\left(\frac{\partial \alpha}{\partial \delta_{a_o}}\right)_{C_L} \delta_{a_o}} \left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L}' \tag{17}$$

The effectiveness of the aileron-balancing-tab combination $\left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L}'$ must now be expressed in terms of the tab ratio. The lift coefficient may be expressed as

$$\left.\begin{aligned} C_L &= C_{L_\alpha}\left[\alpha - \left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L} \delta_a - \left(\frac{\partial \alpha}{\partial \delta_t}\right)_{C_L} \delta_t\right] \\ &= C_{L_\alpha}\left\{\alpha - \left[\left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L} + \left(\frac{\partial \alpha}{\partial \delta_t}\right)_{C_L} \frac{\partial \delta_t}{\partial \delta_a}\right]\delta_a\right\} \\ &= C_{L_\alpha}\left[\alpha - \left(\frac{\partial \alpha}{\partial \delta_a}\right)' \delta_a\right] \end{aligned}\right\} \tag{18}$$

where

$$\left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L}' = \left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L} + \left(\frac{\partial \alpha}{\partial \delta_t}\right)_{C_L} \frac{\partial \delta_t}{\partial \delta_a} \tag{19}$$

Equations (10), (11), (13), (17), and (19) can be solved simultaneously to obtain the required rate of tab deflection with aileron deflection to give any desired $C_{h_{\delta_a}}'$. The resulting expression in terms of known characteristics of the airplane with the original aileron is

$$\frac{\partial\delta_t}{\partial\delta_a} = \frac{C_{h_{\delta_a}}' - \left[C_{h_{\delta_a}}'' + 57.3\,\frac{\overline{b}}{b}\,\frac{\left(\frac{pb}{2V}\right)_o}{\left(\frac{\partial\alpha}{\partial\delta_{a_o}}\right)_{C_L}\delta_{a_o}}\left(\frac{\partial\alpha}{\partial\delta_a}\right)_{C_L} C_{h_\alpha}''\right]}{C_{h_{\delta_t}}'' + 57.3\,\frac{\overline{b}}{b}\,\frac{\left(\frac{pb}{2V}\right)_o}{\left(\frac{\partial\alpha}{\partial\delta_{a_o}}\right)_{C_L}\delta_{a_o}}\left(\frac{\partial\alpha}{\partial\delta_t}\right)_{C_L} C_{h_\alpha}''} \tag{20}$$

The effectiveness of the aileron-balancing-tab combination can be found from equation (19). The deflection of the new aileron required to give the same rate of roll as the original aileron deflected $\pm\delta_{a_o}$ degrees can be found from equation (16) as follows:

$$\delta_a = \pm\frac{\left(\frac{\partial\alpha}{\partial\delta_{a_o}}\right)_{C_L}}{\left(\frac{\partial\alpha}{\partial\delta_a}\right)_{C_L}'}\,\delta_{a_o} \tag{21}$$

The maximum tab deflection, which should be normally limited to less than 20°, can be found from the following expression:

$$\delta_{t_{max}} = \frac{\partial\delta_t}{\partial\delta_a}\,\delta_{a_{max}} \tag{22}$$

The expressions derived in this paper can be used to calculate aileron-balancing-tab characteristics for any airplane, even though the characteristics of the airplane with an original aileron are now known, provided that the factor k, which is proportionate to the damping in roll, can be correctly estimated.

For illustrative purposes, certain characteristics of a given airplane with original ailerons are assumed to be as follows:

$$\frac{c_{a_o}}{c} = 0.15$$

$$b = 37.3 \text{ feet}$$

$$\bar{b} = 27.3 \text{ feet}$$

$$\left(\frac{pb}{2V}\right)_{o_{max}} = 0.09 \text{ when } \delta_{a_o} = \pm 15^\circ$$

With these characteristics known, the rate of change of tab deflection with aileron deflection required to give any $C_{h_{\delta_a}}{}'$ is, from equation (20),

$$\frac{\partial \delta_t}{\partial \delta_a} = \frac{C_{h_{\delta_a}}{}' - \left[C_{h_{\delta_a}}{}'' + 0.664\, C_{h_\alpha}{}'' \left(\frac{\partial \alpha}{\partial \delta_a}\right)_{C_L}\right]}{C_{h_{\delta_t}}{}'' + 0.664\, C_{h_\alpha}{}'' \left(\frac{\partial \alpha}{\partial \delta_t}\right)_{C_L}} \qquad (23)$$

DISCUSSION

Calculations based on the preceding analysis have been made to determine the various aileron-balancing-tab combinations that, for the assumed airplane, will give the same maximum rate of roll as the original unbalanced ailerons but will produce zero change in aileron hinge moment with aileron deflection $(C_{h_{\delta_a}}{}' = 0)$.

Section data for plain flaps and tabs on the NACA 0009 airfoil, taken from reference 3 have been used for the calculations. For ailerons smaller than a 0.30c aileron, the tab data have been extrapolated from the curves of this reference.

The results of the calculations are presented in figure 2. The aileron deflection required to give the same maximum rate of roll as the original aileron, the rate of change of tab deflection with aileron deflection to give $C_{h_{\delta_a}}' = 0$, and the maximum tab deflection have been plotted as functions of aileron chord for three sizes of tab. The maximum aileron deflection was assumed to be that required to produce $pb/2V$ equal to 0.09 and, consequently, the maximum tab deflection was determined for this condition. Because, at the maximum aileron deflections calculated for the illustrative problem, tabs become relatively ineffective in reducing aileron hinge moments when deflected much beyond 20°, this deflection has been arbitrarily assumed as the allowable limit for the deflection of the tab. The left extremities of the curves of figure 2 have been determined accordingly. For the given airplane, therefore, the smallest-chord aileron capable of producing $pb/2V = 0.09$ with $C_{h_{\delta_a}}' = 0$ when the airplane is rolling is: (a) a 0.16c aileron with a $0.30c_a$ tab, (b) a 0.20c aileron with a $0.20c_a$ tab, or (c) a 0.25c aileron with a $0.10c_a$ tab. Ailerons with chords smaller than those quoted will require tab deflection greater than 20° for zero hinge moment at the maximum aileron deflection. Experimental data presented in figures 13, 16, and 19 of reference 4 indicate that, if the aileron deflection is large (45° for a $0.10c_f$ tab, 35° for a $0.20c_f$ tab, and 25° for a $0.30c_f$ tab), the tab is still effective when deflected as much as 30° in a direction opposed to the aileron deflection. This fact has been verified experimentally by unpublished data from recent tests. Careful consideration should be given, therefore, to the maximum allowable tab deflection for each particular airplane.

Tabs of a given ratio of tab chord to aileron chord, in the range of aileron chords investigated, are more effective in reducing the hinge moments of large-chord ailerons than of small-chord ailerons. Figure 2 shows that a greater rate of tab-to-aileron deflection is required on small-chord ailerons than on large-chord ailerons.

The effect of the hinge moment caused by the tab link on the characteristics of aileron-balancing-tab systems is shown in figure 2. The solid-line curves of this figure were computed by assuming a parallel linkage system, a procedure that is the equivalent of assuming for the purpose of calculations that $\partial\delta_t/\partial\delta_a = -1$. The dashed-line curves of figure 2 were computed with all effects of the tab link entirely neglected. Both curves, however, include the effect of rolling velocity. The increment between the dashed-line and the solid-line curves, therefore, indicates the magnitude and the direction of the effect of neglecting the hinge moment caused by the tab link. An inspection of these results indicates that, when the balancing-tab link is such that the aileron hinge moments are reduced by the link, the rate of change of tab deflection with aileron deflection required to give complete balance is slightly greater than would be computed if the effect of the link were neglected. This condition occurs because the balancing tab parameter $Ch_{a_{\delta_t}}$ is reduced more than the aileron parameter $Ch_{a_{\delta_a}}$ because $Ch_{t_{\delta_t}}$ is greater than $Ch_{t_{\delta_a}}$. (See equation (5).)

The rate-of-deflection curves and, consequently, all the solid-line curves of figure 2 should be interpreted, therefore, according to the discussion in the preceding paragraph because, as has previously been pointed out, in order to simplify the calculations, the effect of the tab link was approximated to be that for $\partial\delta_t/\partial\delta_a = -1$. The solution is, therefore, exact only for ailerons requiring this rate of tab deflection. Aileron-tab combinations for which the required rate of tab deflection (fig. 2) is greater than -1 will not be quite completely balanced with the deflection rate calculated. On the other hand, aileron-tab combinations for which the required deflection rate is less than -1 will be slightly overbalanced with the calculated rate of tab deflection. The true rate of tab deflection should be very slightly greater or smaller by an amount proportional to the increment between the dashed-line and the solid-line curves and to the deviation of calculated rate from the assumed rate of -1. For all practical purposes, however, this correction is negligible and the solid-line curves represent a solution sufficiently accurate for design calculations. The characteristics of any particular balancing-tab system can be easily altered by an adjustment of the linkage arms after flight tests have been made to determine final modifications.

CONCLUSIONS

An analysis of the application of balancing tabs to ailerons indicates the following general conclusions:

1. Calculations based on experimental section data have shown that a balancing tab is a feasible and convenient

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means of reducing aileron hinge moments to zero or to any desired magnitude.

2. Because the over-all lift effectiveness is less for an aileron-balancing-tab combination than for a plain aileron, the chord, the span, or the maximum deflection must be greater for the balanced aileron than for the plain aileron to produce a given maximum rate of roll.

3. In the range of aileron chords investigated, balancing tabs of a given ratio of tab chord to aileron chord were more effective in reducing the hinge moments of large-chord ailerons than of small-chord ailerons.

4. The effect of the tab link on the aileron hinge-moment characteristics can be satisfactorily approximated. For conventional balancing tabs, the tab linkage tends to reduce, algebraically but not necessarily numerically, the aileron hinge moments that would occur if the tab were fastened to the aileron and not to the main airfoil. Because of this fact, the tab link tends to increase the rate of change of tab deflection with aileron deflection necessary for any given amount of balance.

5. The minimum-chord tab that can be used with any chord aileron is limited by the condition that the tab should not be deflected beyond the limit of its effective range.

6. Final modifications in the characteristics of an aileron-balancing-tab system, as indicated desirable by flight tests, can be easily made by altering the rate of tab deflection by changing a link arm of the system.

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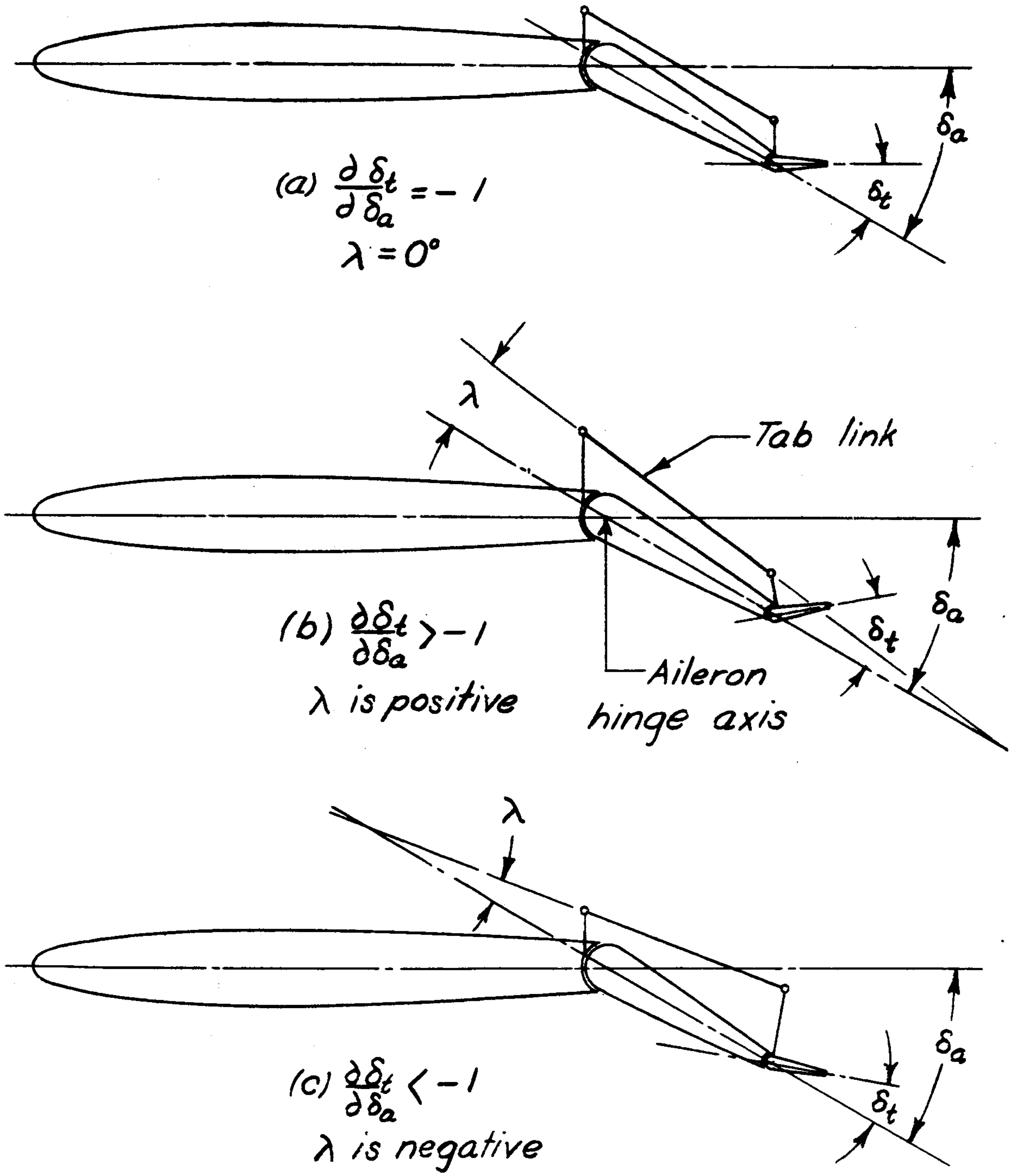

FIGURE 1.- Various balancing-tab linkage systems for ailerons.

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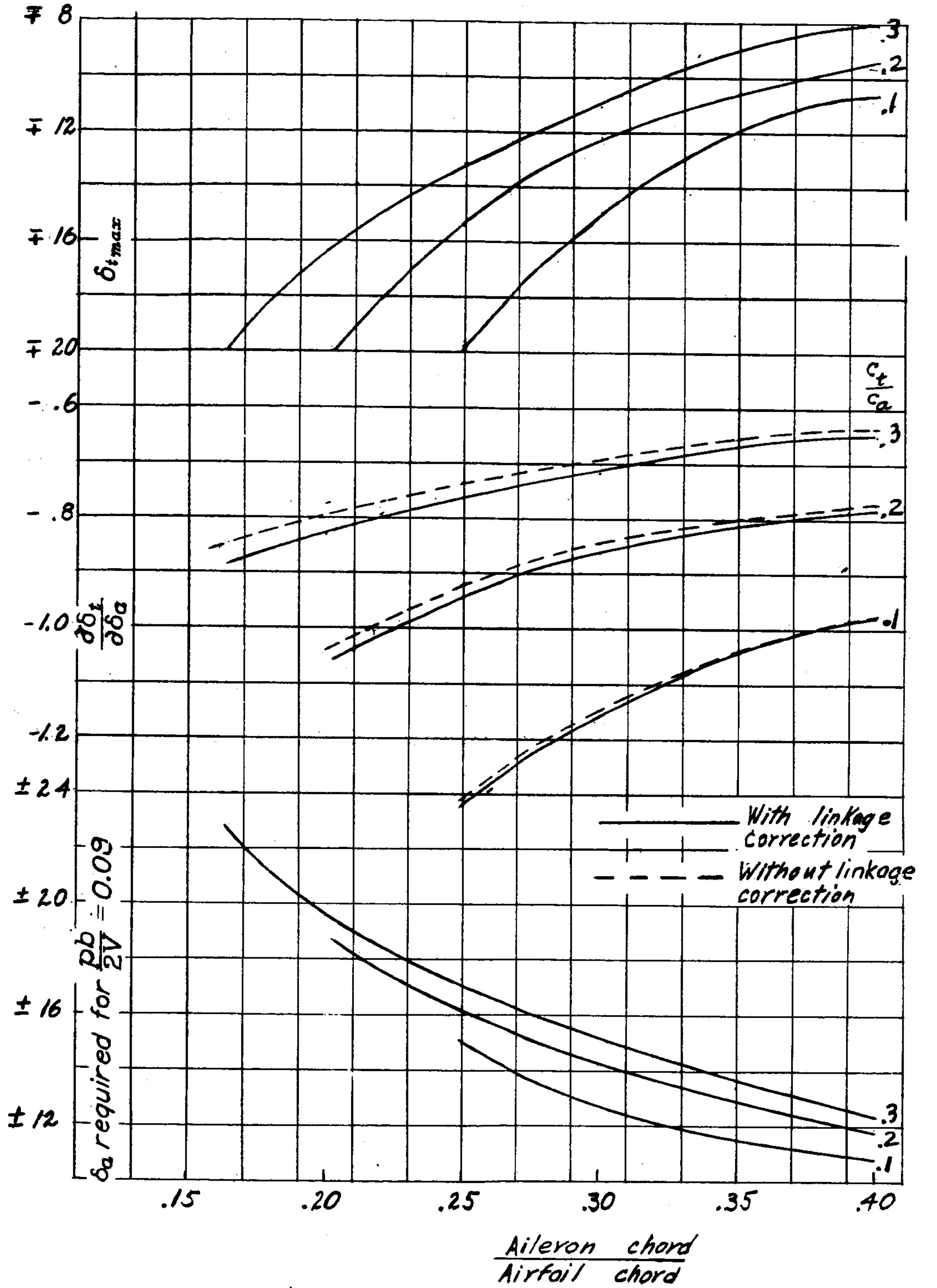

Figure 2. - Characteristics of ailerons with balancing tab deflected to give $C_{h_{\delta_a}}{}' = 0$ when airplane is rolling; based on section data for NACA 0009 airfoil.